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ELECTRIC MACHINE DRIVE HAVING SENSORLESS CONTROL

Technical Field

The present invention relates generally to electric machine drives and more particularly to an electric machine drive having sensorless control.

Background

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The elimination of rotor position, velocity, and flux sensors from electric machine drives has significant cost, reliability, and competitive advantages. Chief among these is the reduction in the cost associated with these expensive sensors and their associated wiring and connectors, which together are one of the leading causes of problems in electric machines and one of the most expensive to fix. These sensors and their associated wiring and connectors are also a major reliability concern due to their inherent fragile nature and sensitivity to harsh environments. The elimination of these sensors also provides a competitive advantage beyond those related to cost and reliability by allowing higher performance and efficiency control techniques to be used in applications where lower performance control techniques would have been used previously due to a lack of these sensors.

The control techniques used to eliminate rotor position, velocity or flux sensors are often described as "sensorless control." At high rotor

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speeds and excitation frequencies, these techniques have shown a lot of promise and have achieved some commercial success. Their inability to run at lower speeds and excitation frequencies excludes these techniques from being used in applications that require operation in these regions, including industrial drives, consumer appliances, and automotive applications (for example, electric traction drives for electric or fuel cell powered vehicles, hybrid electric vehicles, and electric power assisted steering).

To overcome the inability of operating at low rotor speeds and excitation frequencies, a second class of "sensorless controls" techniques has been developed that eliminates the dependence on the fundamental excitation of the electric machine. These techniques use a separate, high frequency sensing excitation applied to the machine in addition to fundamental excitation. There are many forms that the sensing excitation can take, but a fundamental requirement for those techniques to work is that the electric machine must have some form of saliency. For rotor position or velocity estimation, the saliency must have been related to and move when the rotor of the machine moves. For flux estimation, the saliency typically has some saturation-related dependence and hence contains information related to the position of the flux in the machine. Some examples of these machine types include synchronous reluctance machines, buried permanent magnet machines, switch reluctance machines, and salient pole synchronous machines.

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Other machine types, for example induction machines, do not inherently have significant rotor position dependent saliencies present. In fact, it is often one of the design goals for machines such as these to minimize the magnitudes of the saliencies present. Due to this lack of an inherent rotor position dependent saliency, creating a saliency in these types of machines without significantly affecting the fundamental operation and torque production of the machine is necessary before rotor position or velocity "sensorless control" can be implemented.

Many methods are used to modify or design an induction machine rotor with a rotor position dependent saliency. For example, one method to create a rotor position dependent saliency is to vary the width of the rotor bar slot openings in a repeating manner. The variable width slot openings create a saliency by modulating the reluctance seen by the leakage flux as a function of the rotor position. The variation in width is done in such a way so that a complete cycle of the variation has a period equal to the pole pitch of the machine. Such a period results in a coupling between the saliency and the fundamental of the machine stator windings.

A second method used to create a rotor position dependent saliency is the modify the depth of fill that the rotor bars occupy in the rotor bar slot openings in a repeating pattern with a period again equal to the pole pitch of the machine. This creates a saliency due to the fact that the aluminum

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or copper occupying the rotor bar slot openings will have eddy currents induced in them due to the high frequency sensing signal injected into the machine for the "sensorless control." Because the amount of this fill in the rotor bar slot openings varies around the circumference of the rotor, the amount of eddy currents induced varies and produces the appearance of a high frequency saliency. This is akin to the use of a double rotor cage to increase the amount of starting line torque in line-started induction machines.

A third method of creating a rotor position dependent saliency is to vary the cross-sectional area of the rotor bars, thereby causing the rotor resistance to have a spatial dependence. One of the distinguishing features of this method from the other methods currently used for creating a rotor position dependent saliency is that it creates the saliency using the rotor resistance, whereas the other methods create a saliency by causing the leakage inductance to vary. As with the other methods for creating a saliency, the variation in rotor bar cross-sectional area is done so that it repeats every pole pitch of the machine.

A fourth method for creating a rotor position dependent is to create a saliency by selecting the number of rotor bars and stator slots so that their combination results in the desired saliency. For example, the combination of 28 rotor bars and 24 stator slots results in a rotor position dependent saliency that repeats 4 times around the circumference of the machine and would have a period

equal to the pole pitch of the machine in a 4 pole machine.

The methods listed previously for creating a rotor position dependent saliency share several disadvantages in the way and type of saliency they create. First, all of the methods tie the desired saliency to the torque producing mechanism of the machine. Since the rotor bars play a fundamental role in the torque produced by the machine, the sensing and torque producing functions become inherently tied together. Some of the disadvantages of this relationship include increased ripple torque, increased cogging torque, increased sensitivity to saturation, and a limited potential for modification due to the number of rotor bars.

Another significant limitation caused by creating the desired saliency through the rotor bar design is that skewing of the rotor bars, as is often done in induction machines, significantly reduces any saliency created by these methods. Further, these methods tend to create relatively small magnitude saliencies, making it more difficult to use them for "sensorless control."

Summary of the Invention

To overcome some of the disadvantages and
25 limitations of the methods described above, a new
method for creating rotor dependent saliencies in
electric drive machines is presented.

process, manufacturing techniques are greatly simplified, thereby decreasing the costs associated with manufacturing the rotor.

Other objects and advantages of the present invention will become apparent upon considering the following detailed description and appended claims, and upon reference to the accompanying drawings.

Brief Description of the Drawings

Figure 1 depicts a top view of a stator and rotor of an electric machine drive having a plurality of rotor sensing slots according to one preferred embodiment of the present invention;

Figure 2 is an enlarged view of a portion of Figure 1;

Figure 3 depicts a top view of a stator and rotor of an electric motor drive having a plurality of rotor sensing slots according to another preferred embodiment of the present invention;

Figure 4 is an enlarged view of a portion of Figure 3;

Figure 5 depicts a top view of a stator and rotor of an electric motor drive having a plurality of rotor sensing slots according to another preferred embodiment of the present invention;

Figure 6 is an enlarged view of a portion of Figure 5;

Figure 7 depicts a top view of a stator and rotor of an electric motor drive having a plurality of rotor sensing slots according to another preferred embodiment of the present invention; and

5 Figure 8 is an enlarged view of a portion of Figure 7.

Description of the Preferred Embodiment(s)

Referring now to Figures 1 and 2, an electric machine drive 9 having a complete rotor 10 and stator 12 is depicted. The rotor 10 has a plurality of rotor bars 14 uniformly spaced around the rotor 10. Further, the rotor 10 has a plurality of rotor sensing slots 16 uniformly spaced along its outer periphery 18. The sensing slots 16 have a uniform depth and width. The stator 12 has a plurality of stator slots 20.

The number of sensing slots 16, here twenty-eight, is chosen so that their combination with the stator slots 20, here twenty-four, creates a desired saliency. The use of separate sensing slots 16 results in an effective decoupling between the sensing and torque producing functions. This significantly reduces the potential for ripple torque, cogging torque, or saturation effects.

Another major advantage to using separate sensing slots 16 is that the sensing slots 16 do not have to be skewed if the rotor bars 14 are skewed. Instead, the rotor sensing slots 16 may remain parallel to the stator slots 20 (even if the stator

slots 20 are skewed), resulting in a much larger saliency magnitude.

In another preferred embodiment of the present invention, as depicted in Figures 3 and 4, the spacing between the sensing slots 16 is varied in a repeating manner, sinusoidal for example, to create the desired saliency. For example, a period of variation equal to the pole pitch of the electric machine drive 9 would result in strong coupling between the sensing slots 16 and the fundamental of the machine stator windings (not shown), creating a relatively large saliency ideal for "sensorless control." Such a variation is shown in Figures 3 and 4 as a four-pole induction machine. Since the sensing slots 16 are not used for any function other than to create the desired saliency, the number of sensing slots 16, in Figure 3 and 4 being thirty-five slots 16, can be chosen to optimize the desired saliency.

In another preferred embodiment of the present invention, as depicted in Figures 5 and 6, the depth of the sensing slots 16 are varied in a repeating pattern. As an example, a period of variation equal to the pole pitch of the electric drive machine 9 would result in a strong coupling between the sensing slots 16 and the fundamental of the machine stator windings (not shown), creating a large saliency ideal for "sensorless control." Such a variation is depicted Figures 5 and 6 as a four-pole induction machine. As the sensing slots 16 are not used for any function other than to create the

desired saliency, the number of sensing slots 16 can be chosen to optimize the desired saliency.

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A fourth preferred method for creating the desired rotor position dependent saliency using separate sensing slots 16 is depicted in Figures 7 and 8. In this preferred embodiment, the width of the uniformly spaced sensing slots 16 is varied in a repeating pattern. As an example, a period of variation equal to the pole pitch of the machine 9 would result in a strong coupling between the sensing slots 16 and the fundamental of the machine stator windings, creating a relatively large saliency ideal for "sensorless control." A four-pole machine is depicted in Figures 7 and 8. Again, as above, because the sensing slots 16 have no function other than to create the desired saliency, the number of sensing slots 16 can be chosen to optimize the desired saliency.

The advantages to creating a rotor position dependent saliency using separate sensing slots 16 are numerous and significant. First, since the sensing slots 16 are not used for any function other than to create the desired rotor position dependent saliency, the number of sensing slots 16 can be chosen independently of the number of rotor bars 14 and becomes an important design variable. This is in direct contrast to the prior art, wherein the number of rotor bars significantly limits the potential for creating saliency.

Second, as the sensing slots 16 are not tied to the rotor bars 14 in any way, skewing of the

rotor bars 14 does not reduce the saliency magnitude significantly. Instead, the sensing slots 16 can be designed to remain parallel to the stator slots 20, even if the stator slots 20 are skewed, thereby
5 maximizing potential for creating a desired saliency.

Third, the effects of saturation on the saliency is minimized since the fundamental flux near the sensing slots 16 will typically be parallel to the sensing slots 16. This is in contrast to methods
10 listed in the prior art that created a saliency by varying the rotor bar slot openings in some manner. It is well known that leakage flux due to the fundamental excitation causes saturation in these structures at relatively low levels of excitation.

Fourth, the use of sensing slots 16 separates the sensing function from the torque producing mechanism of the machine 9. This significantly increases the ability to create saliency without significantly affecting the
15 fundamental operation of the machine 9, resulting in lower torque ripple and cogging torque.

Finally, the creation of sensing slots can be used equally well in pre-existing or new machine designs. The methods listed in the prior art exhibit
25 significant limitations when applied to pre-existing machines in an attempt to retrofit them for "sensorless control."

A related potential advantage to the use of separate sensing slots 16 is the possibility for
30 simplified manufacturing when compared to most prior

art methods. These methods require keeping track of the orientation of laminations during the assembly process in order to create the desired saliency. The sensing slots 16 of the present invention, on the other hand, can be created during a post-assembly step, thereby significantly reducing the complexity of the assembly process.

While the invention has been described in terms of preferred embodiments, it will be understood, of course, that the invention is not limited thereto since modifications may be made by those skilled in the art, particularly in light of the foregoing teachings. For example, the plurality of sensing slots 16 could be introduced to create rotor position dependent saliency in induction machines, Lundell-type synchronous machines, buried permanent magnet synchronous machines, and surface permanent magnet synchronous machines.

What Is Claimed Is:

1. A method for modifying an electric machine drive rotor having a stator to create rotor position dependent saliency and allow sensorless
5 control, the method comprising the step of:

providing a plurality of sensing slots around the rotor, wherein said plurality of sensing slots create a desired saliency.

2. The method of claim 1, wherein the
10 step of providing a plurality of sensing slots around the rotor, wherein said plurality of sensing slots create a desired saliency comprises the step of providing a plurality of sensing slots uniformly spaced around the rotor, wherein said plurality of
15 sensing slots create a desired saliency.

3. The method of claim 1, wherein the step of wherein the step of providing a plurality of sensing slots around the rotor, wherein said plurality of sensing slots create a desired saliency
20 comprises the step of providing a plurality of sensing slots variably spaced in a repeating manner around the rotor, wherein said plurality of sensing slots create a desired saliency.

4. The method of claim 2, wherein the
25 step of providing a plurality of sensing slots uniformly spaced around the rotor, wherein said plurality of sensing slots create a desired saliency comprises the step of providing a plurality of sensing slots uniformly spaced around the rotor,
30 wherein each of said plurality of sensing slots has a

uniform width and depth around the rotor, and wherein said plurality of sensing slots create a desired saliency.

5 5. The method of claim 2, wherein the
step of providing a plurality of sensing slots
uniformly spaced around the rotor, wherein said
plurality of sensing slots create a desired saliency
comprises the step of providing a plurality of
sensing slots uniformly spaced around the rotor,
10 wherein each of said plurality of sensing slots has a
uniform width around the rotor, wherein the depth of
each of said plurality of sensing slots varies in a
repeating manner around the rotor, and wherein said
plurality of sensing slots create a desired saliency.

15 6. The method of claim 2, wherein the
step of providing a plurality of sensing slots
uniformly spaced around the rotor, wherein said
plurality of sensing slots create a desired saliency
comprises the step of providing a plurality of
20 sensing slots uniformly spaced around the rotor,
wherein each of said plurality of sensing slots has a
uniform depth around the rotor, wherein the width of
each of said plurality of sensing slots varies in a
repeating manner around the rotor, and wherein said
25 sensing slots create a desired saliency.

 7. The method of claim 1, wherein the
step of providing a plurality of sensing slots around
the rotor, wherein said plurality of sensing slots
create a desired saliency comprises the step of
30 providing a plurality of sensing slots around the

rotor in a post-assembly step, wherein said plurality of sensing slots create a desired saliency.

8. The method of claim 1, wherein the step of providing a plurality of sensing slots around the rotor, wherein said plurality of sensing slots create a desired saliency comprises the step of providing a plurality of sensing slots around the rotor, wherein said plurality of sensing slots are coupled with a plurality of stator slots of a stator to create a desired saliency.

9. A sensorless control electric machine drive comprising:

a stator having a plurality of stator slots; and

a rotor having a plurality of rotor sensing slots located along its outer periphery, wherein said plurality of stator slots and said plurality of rotor sensing slots are coupled to create a desired saliency.

10. The sensorless control electric machine drive of claim 9, wherein said plurality of rotor sensing slots are spaced uniformly around the outer periphery of said rotor.

11. The sensorless control electric machine drive of claim 9, wherein said plurality of rotor sensing slots are variably spaced in a repeating pattern around the outer periphery of said rotor.

12. The sensorless control electric machine drive of claim 11, wherein said repeating pattern comprises a sinusoidal repeating pattern.

13. The sensorless control electric machine drive of claim 10, wherein the depth of said plurality of rotor sensing slots is varied in a repeating pattern around said rotor.

14. The sensorless control electric machine drive of claim 10, wherein the width of said plurality of rotor sensing slots is varied in a repeating pattern around said rotor.

15. The sensorless control electric machine drive of claim 10, wherein the sensorless control electric machine drive is selected from the group consisting of a sensorless control induction machine, a Lundell-type synchronous machine, a buried permanent magnet synchronous machine, and a surface permanent magnet synchronous machine.

16. A sensorless control electric machine drive comprising:

a stator having a plurality of stator slots; and

a rotor having a plurality of rotor sensing slots located along its outer periphery, wherein said plurality of rotor sensing slots create a desired saliency.

17. The sensorless control electric machine drive of claim 16, wherein said plurality of rotor sensing slots are spaced uniformly around the outer periphery of said rotor.

machine, a Lundell-type synchronous machine, a buried permanent magnet synchronous machine, and a surface permanent magnet synchronous machine.

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Abstract Of the Disclosure

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A rotor position dependent saliency in a sensorless control electric drive machine (9) introduces a plurality of sensing slots (16) to the outer periphery of a rotor (10). The number, depth, width and location of the sensing slots (16) is chosen to, either directly or through combination with the stator slots (20), create a desired saliency. The use of separate sensing slots (16) results in an effective decoupling between the sensing and torque producing functions in an electric drive motor (9), thereby significantly reducing the potential for ripple torque, cogging torque, or saturation effects. These sensing slots (16) do not have to be skewed if the rotor bars (14) contained within the rotor (10) are skewed; instead they remain parallel to the stator slots (20), resulting in a much larger saliency magnitude.

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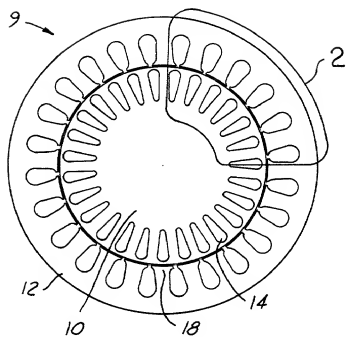


FIG. 1

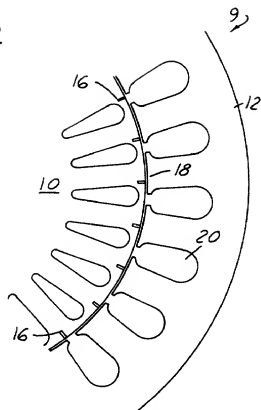


FIG. 2

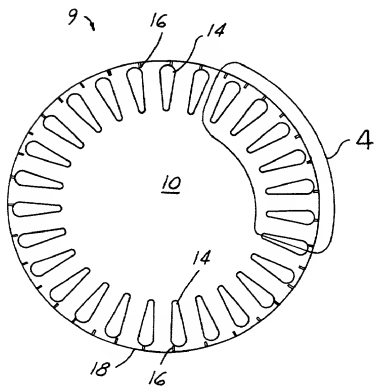


FIG. 3

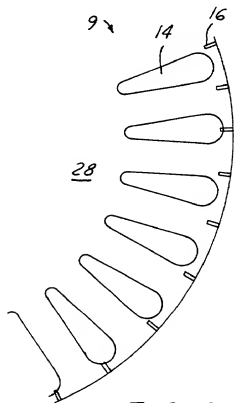


FIG. 4

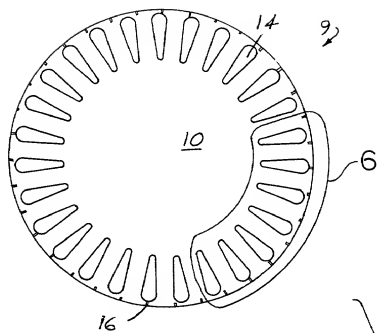


FIG. 5

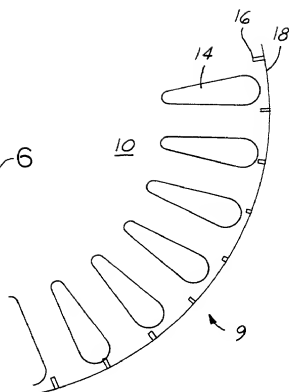


FIG. 6

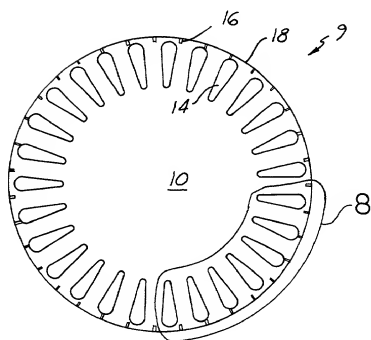


FIG. 7

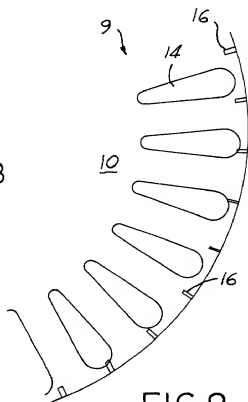


FIG. 8

DECLARATION AND POWER OF ATTORNEY - ORIGINAL APPLICATION

Attorney's Docket No.
200-0163

As a below named inventor, I hereby declare:
My residence, post office address and citizenship are as stated below next to my name;

I verily believe I am the original, first and sole inventor or an original, first and joint inventor of the subject matter that is claimed and for which a patent is sought on the invention entitled

ELECTRIC MACHINE DRIVE HAVING SENSORLESS CONTROL

the specification of which is attached hereto.

I have reviewed and understand the contents of the specification identified above, including the claims.

I acknowledge my duty to disclose information of which I am aware that is material to the examination of this application in accordance with Section 1.56(a), Title 37 of the Code of Federal Regulations; and as to application for patents or inventor's certificate on the invention filed in any country foreign to the United States of America, prior to this application by me or my legal representatives or assigns,

☒ no such applications have been filed, or

☐ such applications have been filed as follows

COUNTRY	APPLICATION NO.	DATE OF FILING (month, day, year)	DATE OF ISSUE (month, day, year)	PRIORITY CLAIMED UNDER 35 USC 119

☐ I hereby claim the benefit under 35 U.S.C. 119(e) of any United States provisional application(s) listed below.

APPLICATION NUMBER(S)	FILING DATE (month, day, year)	<input type="checkbox"/> Additional provisional application numbers are listed on a supplemental priority data sheet PTO/SB/02B attached hereto.

I hereby claim the benefit under 35 U.S.C. § 120 of any United States application(s) or § 365(c) of any PCT International application designating the United States, listed below and, insofar as the subject matter of each of the claims of this application is not disclosed in the prior United States or PCT International application in the manner provided by the first paragraph of 35 U.S.C. § 112, I acknowledge the duty to disclose information which is material to patentability as defined in 37 CFR § 1.56 which became available between the filing date of the prior application and the national or PCT International filing date of this application.

(Application Number) (Filing Date) (Status - patented, pending, abandoned)

(Application Number) (Filing Date) (Status - patented, pending, abandoned)

POWER OF ATTORNEY: As a named inventor, I hereby appoint the following attorney(s) and/or agent(s) to prosecute this application and transact all business in the United States Patent and Trademark Office connected therewith and to act on my behalf before the competent International Authorities in connection with any and all international applications filed by me. (List name and registration number)

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I hereby declare that all statements made herein of my own knowledge are true and that all statements made on information and belief are believed to be true; and further that these statements were made with the knowledge that willful false statements and the like so made are punishable by fine or imprisonment, or both, under Section 1001 of Title 18 of the United States Code, and that such willful false statements may jeopardize the validity of the application or any patent issuing thereon.

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